

# The CLEO-c Research Program

Holger Stöck

*University of Florida, Department of Physics, PO Box 118440, Gainesville, FL 32611-8440, USA*

## Abstract.

In spring 2003, the B physics era ended for the CLEO experiment with a final run at the  $\Upsilon(5S)$  resonance. Over the summer the experiment and the CESR accelerator were modified to operate at lower center-of-mass energies between 3 and 5 GeV. In September 2003 the CLEO-c detector has begun to take its first data at the  $\psi(3770)$  resonance, with which a new era for the exploration of the charmonium sector begins. The CLEO-c research program presented here will include studies of leptonic, semileptonic and hadronic charm decays, searches for exotic, gluonic matter and test for new physics beyond the Standard Model.

## INTRODUCTION

The CLEO-c physics program includes a variety of measurements that will contribute to the understanding of important Standard Model processes as well as provide the opportunity to probe the physics that lies beyond the Standard Model. The dominant themes of this program are measurement of absolute branching ratios for charm mesons with the precision of the order of 1 - 2% (depending upon the mode), determination of charm meson decay constants and of the CKM matrix elements  $|V_{cs}|$  and  $|V_{cd}|$  at the 1 - 2% level and investigation of processes in charm and  $\tau$  decays, that are expected to be highly suppressed within the Standard Model. Hence, a reconfigured CESR electron-positron collider operating at a center of mass energy range between 3 and 5 GeV together with the CLEO detector will give significant contributions to our understanding of fundamental Standard Model properties.

## RUN PLAN AND DATA SETS

From the year 2003 to 2006 the CESR accelerator will be operated at center-of-mass energies corresponding to  $\sqrt{s} \sim 4140\text{MeV}$ ,  $\sqrt{s} \sim 3770\text{MeV}$  ( $\psi''$ ) and  $\sqrt{s} \sim 3100\text{MeV}$  ( $J/\psi$ ). Taking into account the anticipated luminosity which will range from  $5 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$  down to about  $1 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$  over this energy range, the run plan will yield  $3\text{fb}^{-1}$  each at the  $\psi''$  and at  $\sqrt{s} \sim 4140\text{MeV}$  above  $D_s\bar{D}_s$  threshold and  $1\text{fb}^{-1}$  at the  $J/\psi$ . These integrated luminosities correspond to samples of 1.5 million  $D_s\bar{D}_s$  pairs, 30 million  $D\bar{D}$  pairs and one billion  $J/\psi$  decays. As a point of reference, these datasets will exceed those of the Mark III experiment by factors of 480, 310 and 170, respectively. Table 1 summarizes the run plan.

**TABLE 1.** The 3-year CLEO-c run plan

Year	Resonance	Anticipated Luminosity ( $fb^{-1}$ )	Reconstructed Events
1	$\psi(3770)$	$\sim 3$	30M $D\bar{D}$ , 6M tagged $D$
2	$\sqrt{s} \sim 4140MeV$	$\sim 3$	1.5M $D_s\bar{D}_s$ , 0.3M tagged $D_s$
3	$\psi(3100)$	$\sim 1$	60M radiative $J/\psi$

In addition, prior to the conversion to low energy a total amount of  $4fb^{-1}$  spread over the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(3S)$  and  $\Upsilon(5S)$  resonances is taken to launch the QCD part of the program. These data sets will increase the available  $b\bar{b}$  bound state data by more than an order of magnitude.

## HARDWARE REQUIREMENTS

The conversion of the CESR accelerator for low energy operation requires the addition of 18 meters of wiggler magnets to enhance transverse cooling of the beam at low energies. 6 of 14 wigglers were installed in summer 2003 with additional 6 wigglers scheduled for installation in 2004. In the CLEO III detector the silicon vertex detector was replaced by a small, low mass inner drift chamber. In addition, the solenoidal field will be reduced to 1.0 T. No other requirements are necessary.

## PHYSICS PROGRAM

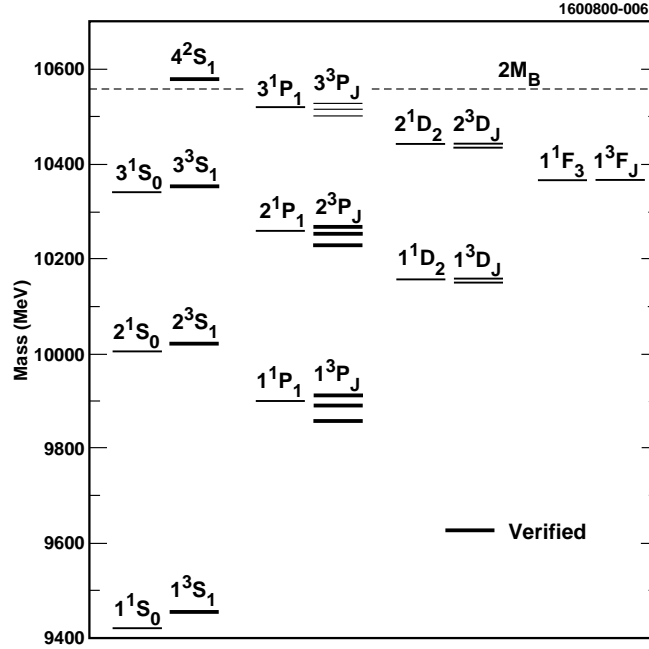
The following sections will outline the CLEO-c physics program. The first section will focus on the Ypsilon spectroscopy, the second section will describe the charm decay program, the third section will give an overview about the exotic, gluonic matter studies and the last section will describe the opportunities for probing of new physics beyond the Standard Model.

### Ypsilon Spectroscopy

From fall 2001 to spring 2003 CLEO has collected  $4fb^{-1}$  of data on the  $\Upsilon$  resonances below the  $\Upsilon(4S)$ , as well as at the  $\Upsilon(5S)$  resonance, which is currently being analyzed. So far, the only established states below  $B\bar{B}$  threshold are the three vector singlet  $\Upsilon$  resonances ( $^3S_1$ ) and the six  $\chi_b$  and  $\chi'_b$  (two triplets of  $^3P_J$ ) that are accessible from these parent vectors via E1 radiative transitions (see Figure 1). By collecting substantial data samples at the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  and  $\Upsilon(3S)$ , CLEO will address a variety of outstanding physics issues.

- Discovery of  $\eta_b$  and Observation of  $h_b$

The  $\eta_b$  is the ground state of  $b\bar{b}$ . Most present theories [1] indicate the best



**FIGURE 1.** Approximate levels of the  $b\bar{b}$  states. The name associated with the spin-parity assignments are  $^1S_0 = \eta_b$ ,  $^3S_1 = \Upsilon$ ,  $^1P_1 = h_b$  and  $^3P_J = \chi_b$  (triplets with  $J = 0, 1, 2$ ).

approach would be the hindered M1 transition from the  $\Upsilon(3S)$ , with which CLEO might have a signal of  $5\sigma$  significance in  $1fb^{-1}$  of data. In the case of the  $h_b$ , CLEO established an upper limit of  $\mathcal{B}(\Upsilon(3S) \rightarrow \pi^+\pi^-h_b) < 0.18\%$  at 90% confidence level [2]. This result, based on  $\sim 110pb^{-1}$ , already tests the theoretical predictions [3] for this transition which range from 0.1 - 1.0%. The resonance run program will measure the mass of the  $h_b$ , assuming the predictions are valid, to  $\sim 5MeV$ .

- Observation of  $1^3D_J$  states

The  $b\bar{b}$  system is unique as it has states with  $L = 2$  that lie below the open-flavor threshold. These states have been of considerable theoretical interest, as indicated by many predictions of the center-of-gravity of the triplet and by a recent review [4]. In an analysis of the  $\Upsilon(3S)$  CLEO data sample the  $\Upsilon(1^3D_2)$  state could already be observed in the four-photon cascade  $\Upsilon(3S) \rightarrow \gamma_1\chi'_b \rightarrow \gamma_1\gamma_2\Upsilon(^3D_J) \rightarrow \gamma_1\gamma_2\gamma_3\chi_b \rightarrow \gamma_1\gamma_2\gamma_3\gamma_4\ell^+\ell^-$ . The mass of the  $\Upsilon(1^3D_2)$  state is determined to  $10161.1 \pm 0.6 \pm 1.6MeV/c^2$  [5].

- Search for glueball candidates in radiative  $\Upsilon(1S)$  decays

The BES collaboration has reported signals for a glueball candidate [6] in radiative  $J/\psi$  decay - a glue-rich environment. Naively one would expect the exclusive radiative decay to be suppressed in  $\Upsilon$  decay by a factor of roughly 40, which implies product branching fractions for  $\Upsilon$  radiative decay of  $\sim 10^{-6}$ . With  $1fb^{-1}$  of data and efficiencies of around 30% one can expect  $\sim 10$  events in each of the exclusive channels, which would be an important confirmation of the  $J/\psi$  studies.

## Charm Decays

The observable properties of the charm mesons are determined by the strong and weak interactions. As a result, charm mesons can be used as a laboratory for the studies of these two fundamental forces. Threshold charm experiments permit a series of measurements that enable direct study of the weak interactions of the charm quark, as well as tests of our theoretical technology for handling the strong interactions.

### *Leptonic Charm Decays*

Measurements of leptonic decays in CLEO-c will benefit from the use of fully tagged  $D^+$  and  $D_s$  decays available at the  $\psi(3770)$  and at  $\sqrt{s} \sim 4140 \text{ MeV}$ . The leptonic decays  $D_s \rightarrow \mu \nu$  are detected in tagged events by observing a single charged track of the correct sign, missing energy, and a complete accounting of the residual energy in the calorimeter. The clear definition of the initial state, the cleanliness of the tag reconstruction, and the absence of additional fragmentation tracks make this measurement straightforward and essentially background-free. This will enable measurements of the yet barely known leptonic decay rates for  $D$  and  $D_s$  to a precision of 3 - 4% and will allow for incisive checks of theoretical calculations of the decay constants  $f_D$  and  $f_{D_s}$  at the 1 - 2 %. Table 2 summarizes the expected precision in the decay constant measurements.

**TABLE 2.** Expected decay constants errors for leptonic decay modes

Decay Mode	Decay Constant	Decay Constant Error %	
		PDG 2000	CLEO-c
$D^+ \rightarrow \mu^+ \nu$	$f_D$	Upper Limit	2.3
$D_s^+ \rightarrow \mu^+ \nu$	$f_{D_s}$	17	1.7
$D_s^+ \rightarrow \tau^+ \nu$	$f_{D_s}$	33	1.6

### *Semileptonic Charm Decays*

The CLEO-c program will provide a large set of precision measurements in the charm sector against which the theoretical tools needed to extract CKM matrix information precisely from heavy quark decay measurements will be tested and honed.

CLEO-c will measure the branching ratios of many exclusive semileptonic modes, including  $D^0 \rightarrow K^- e^+ \nu$ ,  $D^0 \rightarrow \pi^- e^+ \nu$ ,  $D^0 \rightarrow K^- e^+ \nu$ ,  $D^+ \rightarrow \bar{K}^0 e^+ \nu$ ,  $D^+ \rightarrow \pi^0 e^+ \nu$ ,  $D^+ \rightarrow \bar{K}^{0*} e^+ \nu$ ,  $D_s^+ \rightarrow \phi e^+ \nu$  and  $D_s^+ \rightarrow \bar{K}^{0*} e^+ \nu$ . The measurement in each case is based on the use of tagged events where the cleanliness of the environment provides nearly background-free signal samples, and will lead to the determination of the CKM matrix elements  $|V_{cs}|$  and  $|V_{cd}|$  with a precision level of 1.6% and 1.7%, respectively. Measurements of the vector and axial vector form factors  $V(q^2)$ ,  $A_1(q^2)$  and  $A_2(q^2)$  will also be possible at the  $\sim 5\%$  level. Table 3 summarizes the proposed branching fractional errors.

**TABLE 3.** Expected branching fractional errors for semileptonic decay modes

Decay Mode	BR fractional error %	
	PDG 2000	CLEO-c
$D^0 \rightarrow K \ell \nu$	5	1.6
$D^0 \rightarrow \pi \ell \nu$	16	1.7
$D^+ \rightarrow \pi \ell \nu$	48	1.8
$D_s \rightarrow \phi \ell \nu$	25	2.8

HQET provides a successful description of the lifetimes of charm hadrons and of the absolute semileptonic branching ratios of the  $D^0$  and  $D_s$  [7]. Isospin invariances of the strong forces lead to corrections of  $\Gamma_{SL}(D^0) \simeq \Gamma_{SL}(D^+)$  in the order of  $\mathcal{O}(\tan^2 \Theta_C) \simeq 0.05$ . Likewise,  $SU(3)_{Fl}$  symmetry relates  $\Gamma_{SL}(D^0)$  and  $\Gamma_{SL}(D^+)$ , but a priori would allow them to differ by as much as 30%. However, HQET suggests that they should agree to within a few percent. A charm factory is the best place to measure absolute inclusive semileptonic charm branching ratios, in particular  $\mathcal{B}(D_s \rightarrow X \ell \nu)$  and thus  $\Gamma_{SL}(D_s)$ .

### *Implications of the Leptonic and Semileptonic Measurements for CKM*

Every weak decay involving leptons depends on both CKM elements and on hadronic matrix elements. As described in the sections above, CLEO-c data can be used for calibrating the theoretical tools that will determine the hadronic terms and for extracting the essential CKM elements.

Combining the leptonic and semileptonic measurements leads to “direct” determinations of the CKM elements  $|V_{cd}|$  and  $|V_{cs}|$ . The results are shown in Table 4. For this table LatticeQCD is assumed and validated across a wide range of charm and onium decay measurements, to which CLEO-c will provide decay constants with 1% accuracy.

**TABLE 4.** Collected results for  $|V_{cd}|$  and  $|V_{cs}|$

Decay Mode	CKM Element	CKM Precision
$D_s \rightarrow \mu^+ \nu$	$ V_{cs} $	1.7
$D_s \rightarrow \tau^+ \nu$	$ V_{cs} $	1.6
$D^0 \rightarrow K^- e^+ \nu$	$ V_{cs} $	1.6
$D^+ \rightarrow \mu^+ \nu$	$ V_{cd} $	2.3
$D^0 \rightarrow \pi^- e^+ \nu$	$ V_{cd} $	1.7

The impact of the entire suite of CLEO-c measurements on the current knowledge of the CKM matrix is summarized in the following paragraphs. Just to remind the reader, the CLEO-c program of leptonic and semileptonic measurements has two components: one of calibrating and validating theoretical methods for calculating hadronic matrix elements, which can then be applied to all problems in CKM extraction in heavy quark physics; and one of extracting CKM elements directly from the CLEO-c data. The

direct results of CLEO-c are the precise determination of  $|V_{cd}|$ ,  $|V_{cs}|$ ,  $f_D$ ,  $f_{D_s}$ , and the semileptonic form factors. The precision knowledge of the decay constants  $f_D$  and  $f_{D_s}$ , together with the rigorous calibration of theoretical techniques for calculating heavy-to-light semileptonic form factors, are required for the direct extraction of CKM elements from CLEO-c. This also drives the indirect results, namely the precision extraction of CKM elements from experimental measurements of the  $B_d$  mixing frequency, the  $B_s$  mixing frequency, and the  $B \rightarrow \pi \ell \nu$  decay rate measurements which will be done by a combination of efforts spread across BaBar, Belle, CDF, D0, BTeV, LHCb, ATLAS and CMS.

In Table 5 the combined projections are presented. In the determination of the CKM elements  $|V_{cd}|$  and  $|V_{cs}|$  from  $B$  and  $B_s$  mixing  $|V_{tb}| = 1$  is used. The tabulation also includes improvement in the direct measurement of  $|V_{tb}|$  itself which is expected from the Tevatron experiments [8].

**TABLE 5.** Combined projections for CKM elements at present and after CLEO-c

Present Knowledge		
$\delta V_{ud}/V_{ud} = 0.1\%$	$\delta V_{us}/V_{us} = 1\%$	$\delta V_{ub}/V_{ub} = 25\%$
$\delta V_{cd}/V_{cd} = 7\%$	$\delta V_{cs}/V_{cs} = 16\%$	$\delta V_{cb}/V_{cb} = 5\%$
$\delta V_{td}/V_{td} = 36\%$	$\delta V_{ts}/V_{ts} = 39\%$	$\delta V_{tb}/V_{tb} = 29\%$
After CLEO-c		
$\delta V_{ud}/V_{ud} = 0.1\%$	$\delta V_{us}/V_{us} = 1\%$	$\delta V_{ub}/V_{ub} = 5\%$
$\delta V_{cd}/V_{cd} = 1\%$	$\delta V_{cs}/V_{cs} = 1\%$	$\delta V_{cb}/V_{cb} = 3\%$
$\delta V_{td}/V_{td} = 5\%$	$\delta V_{ts}/V_{ts} = 5\%$	$\delta V_{tb}/V_{tb} = 15\%$

### Hadronic Charm Decays

The  $D^0$  is the best known of all the charm hadrons. The CLEO and ALEPH experiments by far provide the most precise measurements for the decay  $D^0 \rightarrow K^- \pi^+$ . They use the same technique by looking at  $D^{*+} \rightarrow \pi^+ D^0$  decays and taking the ratio of the  $D^0$  decays into  $K^- \pi^+$  to the number of decays with only the  $\pi^+$  from the  $D^{*+}$  decay detected. The dominant systematic uncertainty is the background level in the latter sample. In both experiments, the systematic errors exceed the statistical errors. By using  $D^0 \bar{D}^0$  decays, and tagging both  $D$  mesons, the background can be reduced to almost zero and the branching ratio fractional error can be improved significantly (see Table 6).

The  $D^+$  absolute branching ratios are determined by using fully reconstructed  $D^{*+}$  decays, comparing  $\pi^0 D^+$  with  $\pi^+ D^0$  and using isotropic spin symmetry. Hence, this rate cannot be determined any better than the absolute  $D^0$  decay rate using this technique. By using  $D^+ D^-$  decays and a double tag technique the background can be reduced again to almost zero which leads to a significant improvement of the branching ratio fractional error (see Table 6).

**TABLE 6.** Expected branching fractional errors for hadronic decay modes

Decay Mode	BR fractional error %	
	PDG 2000	CLEO-c
$D^0 \rightarrow K\pi$	2.4	0.5
$D^+ \rightarrow KK\pi$	7.2	1.5
$D_s \rightarrow \phi\pi$	25	1.9

## Exotic, Gluonic Matter

With approximately one billion  $J/\psi$  produced, CLEO-c will be the natural glue factory to search for glueballs and other glue-rich states using  $J/\psi \rightarrow gg \rightarrow \gamma X$  decays. The region of  $1 < M_X < 3\text{GeV}/c^2$  will be explored with partial wave analyses for evidence of scalar or tensor glueballs, glueball- $q\bar{q}$  mixtures, exotic quantum numbers, quark-gluon hybrids and other new forms of matter predicted by QCD. This includes the establishment of masses, widths, spin-parity quantum numbers, decay modes and production mechanisms for any identified states, an in detail exploration of reported glueball candidates such as the tensor candidate  $f_J(2220)$  and the scalar states  $f_0(1370)$ ,  $f_0(1500)$  and  $f_0(1710)$ , and the examination of the inclusive photon spectrum  $J/\psi \rightarrow \gamma X$  with  $< 20$  MeV photon resolution and identification of states with up to 100 MeV width and inclusive branching ratios above  $1 \times 10^{-4}$ . A Monte Carlo study of inclusive radiative  $J/\psi$  decays in CLEO-c is shown in Figure 2 based on a sample of 60 million  $J/\psi$  decays and assuming  $\mathcal{B}(J/\psi \rightarrow \gamma f_J(2220)) = 8 \times 10^{-4}$ . A monochromatic photon line from the  $J/\psi \rightarrow \gamma f_J(2220)$  decay is clearly seen. The signal efficiency is 24%. With  $10^9$   $J/\psi$  decays, CLEO-c will be able to discover any narrow resonance produced in radiative  $J/\psi$  decays with inclusive branching fractions of order  $10^{-4}$  or greater.

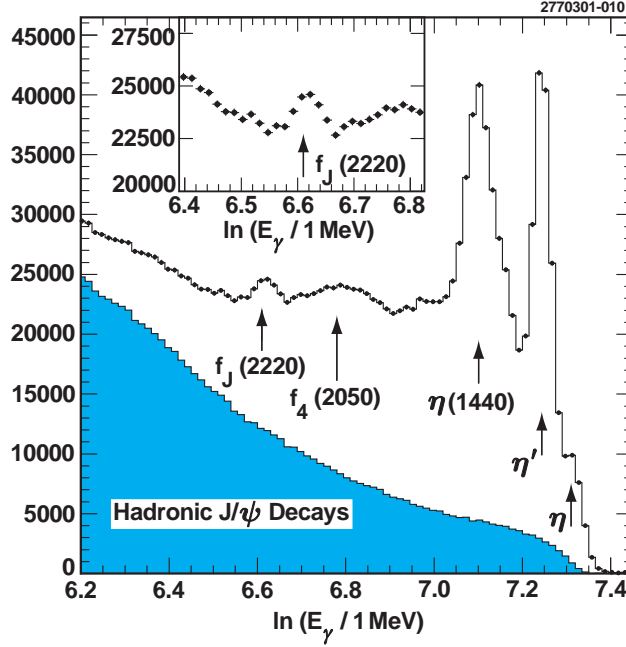
In addition, spectroscopic searches for new states of the  $b\bar{b}$  system and for exotic hybrid states such as  $c g \bar{c}$  will be made using the  $4f b^{-1}$   $\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(3S)$  and  $\Upsilon(5S)$  data sets. Analysis of  $\Upsilon(1S) \rightarrow \gamma X$  will play an important role in verifying any glueball candidates found in the  $J/\psi$  data.

## Charm Beyond the Standard Model

CLEO-c will have the opportunity to probe for new physics beyond the Standard Model. Three highlights -  $D\bar{D}$ -mixing,  $CP$  violation and rare charm decays - are discussed in the following sections.

### $D\bar{D}$ -Mixing

Within the Standard Model (SM), the processes which mediate the decays of charmed quarks and antiquarks can change the “charm” quantum number by one unit,  $\Delta C = 1$ .



**FIGURE 2.** The inclusive photon spectrum from  $J/\psi$  decays from a Monte Carlo simulation in CLEO-c. Signals from  $\eta'$ ,  $\eta(1440)$  and  $f_J(2220)$  are clearly visible. A broad signal from  $f_4(2050)$  production is also evident.

On the other hand, the mixing of  $D^0$  and  $\bar{D}^0$  necessitates changing a charm quark into an anti-charm quark, i.e. the “charm” quantum number must change by two units  $\Delta C = 2$ . This can be arranged in the SM only at one loop level and, therefore, is naturally suppressed. However, new physics (beyond the SM) contributions can generate  $\Delta C = 2$  interactions as well. It is for this reason that neutral meson-antimeson mixing can provide important information about both the SM and new physics beyond the SM. The  $D^0 - \bar{D}^0$  system is particularly interesting in this respect as it is the only system that is sensitive to the dynamics of the bottom-type quarks.

CLEO-c will have the important experimental advantage of operating at the  $D^0 \bar{D}^0$  threshold, where the  $D^0$  and  $\bar{D}^0$  are produced in the state that is quantum mechanically coherent. This allows new and simple methods to be used to measure the  $D^0 - \bar{D}^0$  mixing parameters [9, 10]. Thus, in addition to the “standard” methods of searches for  $D^0 - \bar{D}^0$  mixing, new tools and methods, unique to running at the  $\psi(3770)$  (and higher resonances), become available for studies of these important parameters.

## CP Violation

In addition to indirect  $CP$  violation, both SM and new physics effects can induce different contributions to the decay amplitudes of  $D$  mesons. This phenomenon can be traced back to the appearance of complex-valued couplings (CKM parameters) in the  $\Delta C = 1$  Lagrangian that mediates  $D$  decays and leads to a  $CP$ -violating difference



between decay rates of  $CP$ -conjugated states.

The production process

$$e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$$

produces an eigenstate of  $CP+$ , in the first step, since the  $\psi(3770)$  has  $J^{PC}$  equal to  $1^{--}$ . Now consider the case where both the  $D^0$  and the  $\bar{D}^0$  decay into  $CP$  eigenstates. Then the decays

$$\psi(3770) \rightarrow f_+^i f_+^j \text{ or } f_-^i f_-^j$$

are forbidden, where  $f_+$  denotes a  $CP+$  eigenstate and  $f_-$  denotes a  $CP-$  eigenstate. This is because

$$CP(f_\pm^i f_\pm^j) = (-1)^\ell = -1$$

for the  $\ell = 1$   $\psi(3770)$

Hence, if a final state such as  $(K^+K^-)(\pi^+\pi^-)$  is observed, one immediately has evidence of  $CP$  violation. Moreover, all  $CP+$  and  $CP-$  eigenstates can be summed over for this measurement. This measurement can also be performed at higher energies where the final state  $D^{*0}\bar{D}^{*0}$  is produced. When either  $D^*$  decays into a  $\pi^0$  and a  $D^0$ , the situation is the same as above. When the decay is  $D^{*0} \rightarrow \gamma D^0$  the  $CP$  parity is changed by a multiplicative factor of -1 and all decays  $f_+^i f_-^j$  violate  $CP$  [11]

### *Rare Charm Decays*

Rare decays of charmed mesons and baryons provide “background-free” probes of new physics effects. In the framework of the Standard Model (SM) these processes occur only at one loop level. SM predicts vanishingly small branching ratios for these processes because of the absence in the SM of the super-heavy bottom-type quark supplemented by almost perfect GIM cancellation between the contributions of strange and down quarks. This is very different from the familiar case of bottom quark decays where the top quark contribution dominates the decay amplitude. It also makes the SM predictions for these transitions very uncertain, as the perturbative GIM cancellation mechanism is not effective for soft, long-distance contributions. In addition, in many cases annihilation topologies also give sizable contribution. At the end, any anomalous enhancement of a given branching ratio would have to be compared to the (dominant long-distance) SM amplitude. Fortunately, several model-dependent estimates exist indicating that the SM predictions for these processes are still far below current experimental sensitivities. Some examples are given in [12, 13]. From there it also follows that experiments which can measure rare  $D$  decay branching ratios at the level of  $10^{-6}$ , such as CLEO-c, will start to confront models of new physics in an interesting way.

## **SUMMARY**

The high-precision charm and quarkonium data will permit a broad suite of studies of weak and strong interaction physics. In the threshold charm sector measurements are

uniquely clean and make possible the unambiguous determinations of physical quantities discussed above. CLEO-c will utilize a variety of tools, namely  $J/\psi$  radiative decays, two-photon collisions (using almost real, as well as highly virtual space-like photons), deep inelastic Coulomb scattering and continuum production via  $e^+e^-$  annihilation to obtain significant new information on the spectrum of hadrons, both normal and exotic, and their decay channels. A quantitative improvement can be expected not only from the large accumulated statistics, but also from combining the results obtained using all these tools together with the results from the  $\Upsilon$  resonance runs. The significance of this is better sensitivity, reduced systematics and a better chance to obtain a coherent picture of the hadron sector.

## ACKNOWLEDGMENTS

I am delighted to acknowledge the invaluable contributions of many individuals to the development of the CLEO-c and CESR-c program and the outstanding contributions of my CLEO colleagues over the life of the experiment. The experimental aspects of this program are based on their effort and experience.

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